Quantum dot lasers based photonics integrated circuits

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Abstract: Photonic integrated circuits enable energy efficient and compact technologies for modern information communications. Here, we explore semiconductor epitaxial quantum dots lasers on silicon and demonstrate their high suitability for addressing the important issues associated to photonic integration on silicon.

Keywords: *epitaxial quantum-dot lasers, optical feedback, 4-wave mixing, laser theory, silicon photonics.*

Photonic integrated circuits (PICs) enable numerous high performance and compact technologies for information communication technologies [1]. One reason for silicon-PIC systems is the availability of manufacturing approaches based on modern nanofabrication techniques. Another is the potential for miniaturization of optoelectronic components to be integrated amongst other with complementary functionalities that is of first importance for future quantum information systems. In this context, quantum dot (QD) lasers are seen as crucial building blocks that can be used as energy efficient light transmitters, single-photon sources, and optical translators or inductors [2]. QDs are semiconductor nanostructures of a few nanometers wide whereby the atom-like density of states creates various phenomena based on quantum mechanics. Thus, confining electrons and holes in such nano-sized particles is meaningful for the realization of high performance photonic devices [3]. Recently, it was shown that the direct growth of QDs with III-V materials on silicon does exhibit a strong potential to overcome the high costs of the heterogeneous integration [4]. In this context, epitaxial QD lasers on silicon have demonstrated record performance including a few milliamp threshold currents, continuous wave operation at high temperature, long device lifetimes, relatively low intensity noise, narrow spectral line, and large level of reflection insensitivity, amongst many others [4]. In this work, we provide new findings by exploring the dynamic and nonlinear properties of passively QD mode-locked lasers (MLL) directly grown on silicon as well as the importance of 4-wave mixing effect in epitaxial nanostructures on silicon.

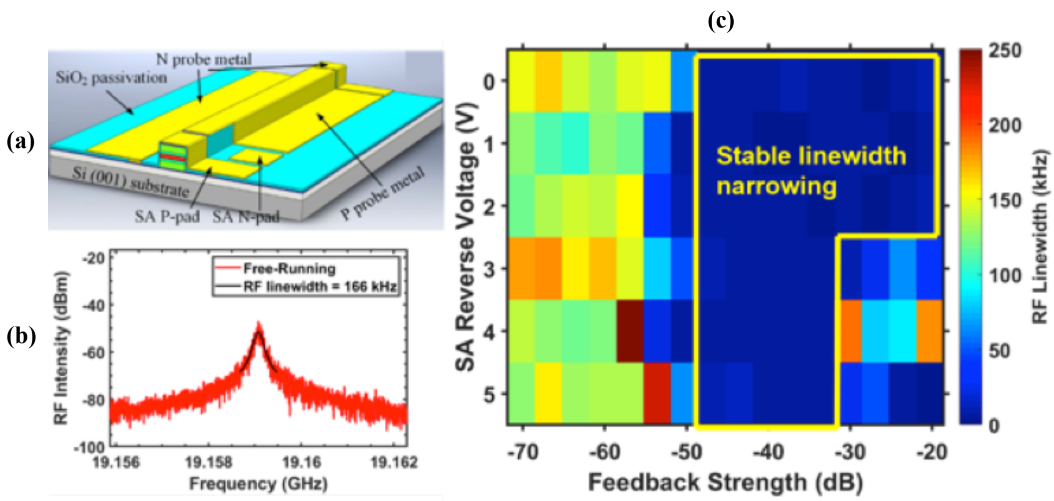

Figure 1. (a) Schematic of QD mode-locked laser (MLL) directly grown on silicon; (b) RF linewidth of ~160 kHz under optimum free-running condition (c) Mapping illustrating the optical feedback stabilization of the radiofrequency (RF) linewidth with respect to the feedback strength and the SA reverse voltage.

Figure 1(a) displays the QD MLL directly grown on a CMOS compatible silicon substrate by solid-source molecular beam epitaxy [5]. The total length of the QD MLL is 2048 microns, which corresponds to a 20 GHz fundamental repetition frequency. The ridge width is 5 microns with a saturable absorber (SA) section of 8% of the cavity. The isolation length between the gain and the SA is 10 microns with an isolation resistance around 15 kΩ. The active region

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of the device consists of a five-layer chirped InAs/InGaAs dots-in-a-well structure spaced by 37.5 nm thick p-type modulation doped GaAs barrier layers. Fig. 1(c) displays the optical feedback stabilization of the radiofrequency (RF) linewidth with respect to the feedback strength and the SA reverse voltage. Results show that when the epitaxial QD MLL is driven into the stable resonant feedback condition [5], the RF linewidth is stabilized as depicted by the wide blue area. Under the best conditions, the RF linewidth is reduced down to about 4 kHz instead of ~160 kHz (Fig. 1(b)) in the free running case (w/o stabilization), which would result in a significant reduction of the peak-to-peak timing jitter from about 60 to 9 fs/cycle. This linewidth narrowing can be further improved by considering a shorter external stabilization loop, which is promising for designing high performance optical clocks and frequency comb generators in future large-scale PICs on silicon.

On the other hand, QDs exhibit large optical nonlinearities owing to the fast carrier-carrier and carrier-phonon scatterings. Previous works revealed that fast 4-wave mixing in QD semiconductor optical amplifiers was obtained through deeper spectral holes originating from the fast carrier scattering [6]. Using a microscopic level model including the quantum mechanical electron-hole polarization, optical nonlinearities in epitaxial QD lasers on silicon is analyzed [7]. To do so, we extract the relevant 4-wave-mixing coefficient $\chi^{(3)}$ from pump-probe laser measurements and connect to multimode semiclassical laser theory. For instance, with the injection of a laser field at the probe mode, one sees the rise of a signal intensity, as depicted in Fig. 2(a). The laser experiments yield some differences from the amplifier ones, as illustrated in Fig. 2(b). The differences arise because of gain saturation by the pump and probe intracavity fields. For small 4-wave mixing susceptibility, mode competition can dominate the generation of the signal. Then, increasing the probe intensity will depress the signal intensity as shown by the black curve in Fig. 2(b), for $\chi^{(3)}=2.2 \times 10^{-20}$ m^2/V^2. With a higher 4-wave mixing susceptibility, e.g. $\chi^{(3)}=2.2 \times 10^{-19}$ m^2/V^2, there is a range of injected probe intensities where the 4-wave mixing gain exceeds the attenuation from mode competition and one sees an increase in signal intensity with increasing injected probe power. Eventually, the signal power drops, when the 4-wave mixing gain can no longer overcome the mode competition (red curve). In the rare situation of a larger 4-wave mixing susceptibility, one may even encounter the situation of 4-wave mixing gain to exceed the cavity losses. Then lasing by 4-wave mixing can occur, as depicted by the 'S' shape blue curve for $\chi^{(3)}=2.2 \times 10^{-18}$ m^2/V^2. These results predict that optical nonlinearities in epitaxial QDs on silicon provide a strong mechanism for self-mode-locking and will be very promising as building blocks for quantum information systems.

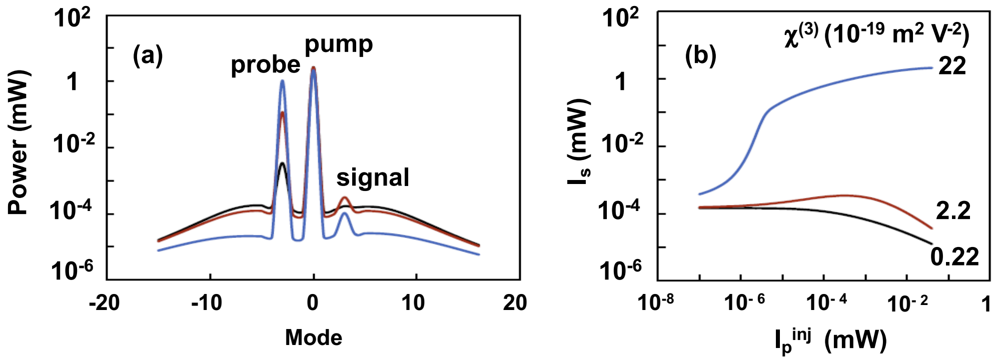

Figure 2. (a) Intracavity power versus mode number for injection intensity of 4× 10^{-2} mW and injected probe intensities ranging from 10^{-6} mW (black), 10^{-4} mW (red) to 10^{-2} mW (blue). The curves are computed assuming 4-wave mixing susceptibility $\chi^{(3)}=2.2 \times 10^{-19}$ m^2/V^2; (b) Signal power versus injected probe power for three different 4-wave mixing susceptibilities $\chi^{(3)}$.

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